

Twenty-Five Years of Progress in the Three-Nucleon Problem

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Abstract. Twenty-five years ago the International Few-Body Conference was held in Quebec City. It became very clear at that meeting that the theoretical situation concerning the ^3He and ^3H ground states was confused. A lack of computational power prevented converged brute-force solutions of the Faddeev or Schrödinger equations, both for bound and continuum states of the three-nucleon systems. Pushed by experimental programs at Bates and elsewhere and facilitated by the rapid growth of computational power, converged solutions were finally achieved about a decade later. Twenty-five years ago the first three-nucleon force based on chiral-symmetry considerations was produced. Since then this symmetry has been our guiding principle in constructing three-nucleon forces and, more recently, nucleon-nucleon forces. We are finally nearing an understanding of the common ingredients used in constructing both types of forces. I will discuss these and other issues involving the few-nucleon systems and attempt to define the current state-of-the-art.

INTRODUCTION

The purview of my talk is progress that has been made in our understanding of the three-nucleon systems and of the dynamics that underlies that understanding. My emphasis will be on the theoretical side. My reference point in time is 1974, the date when Bates first delivered beam for an experiment. I will survey that progress by referring to two other significant events that occurred in 1974. One of these is personal: I attended the International Few-Body Conference held that year in Quebec City, Canada [1]. The second event is the genesis in that year of three-nucleon forces (3NFs) based on chiral-symmetry considerations [2].

On a personal note it is always a pleasure to return to MIT, where I was a post-doc. Looking back at my work during that period, I find that almost everything dealt with electron scattering, a result of the influence of Bates on the young theorists in the Center for Theoretical Physics. Part of that work involved relativistic corrections to the charge densities of few-nucleon systems, and that motivated my attendance at the Quebec meeting.

There are basically three reasons why three-nucleon physics has become a subfield in its own right. The first is that the trinucleons are rich, nontrivial, and “simple” nuclear systems, and understanding their properties is a minimal criterion for success in this area. The word “simple” in this context means that we are capable of performing the very difficult calculations of three-nucleon properties. Indeed, in recent years we have not only succeeded in performing these calculations, but have achieved an understanding of most of the basic trinucleon properties [3,4].

The second reason is the classic and original goal of the field: using these systems to sort out and refine our understanding of the nuclear force. This is the most important remaining aspect of the problem, which has been greatly aided in recent years by chiral perturbation theory (χ PT). Much of our theoretical and experimental attention has been directed at 3NFs, because trinucleon properties show relatively little sensitivity to the details of modern N - N forces. Our remaining problems (though few) are likely due to our lack of understanding of 3NFs [5].

Finally, the lovely techniques used in this field are fun to work with, and this attraction has seduced two generations of theorists. Our efforts have led to the very successful application of few-body methods to heavier systems, which goes far beyond even the dreams of 1974, as shown at this symposium by Vijay Pandharipande.

My strongest impressions of the Quebec meeting are that the field was in a state of confusion. Many calculational techniques were in use, each giving a different answer to the same problem, the ^3H bound-state energy. Faddeev methods, hyperspherical expansions, variational bounds, and separable approximations all had their practitioners [1]. There was a 10-20% uncertainty (~ 1 -2 MeV) in the ^3H binding energy, implying that most (in retrospect, all) of the calculations were not converged. The situation was similar with respect to scattering calculations. In order to achieve convergence one requires brute-force computational resources on a scale that would not be available for another decade.

NUCLEAR FORCES

The genesis of the computational problem is the spin of the nucleon. Contrary to much folklore, nuclear physics is difficult not because the force is complicated (in shape), but because it is complex (i.e., it has many components). The origin of the problem is the spin and parity of the pion: $J^\pi = 0^-$. The π -nucleon vertex must have a complementary pseudoscalar structure in order to conserve angular momentum and parity, and the dominant form ($\sim 1^+ \cdot 1^-$) is $\vec{\sigma}_N \cdot \vec{q}$, where $\vec{\sigma}_N$ is the nucleon (Pauli) spin and \vec{q} is the pion momentum. This leads immediately to a tensor component of the force (part of the one-pion-exchange potential (OPEP)), which dominates interactions in few-nucleon systems. Indeed, $\langle V_{\text{OPEP}} \rangle$ is roughly 75% of the total potential energy. This spin dependence, together with isospin dependence, accounts for the complexity. Each nucleon has $2 \cdot 2 = 4$ spin-isospin components, implying that there are roughly $(4)^2 = 16$ such components in the

N - N force, which is indeed exemplified by the 18 components of the recent AV18 potential [6]. Dealing with these complexities, in addition to the 3 continuous coordinates specifying the positions of 3 nucleons, is a formidable numerical problem.

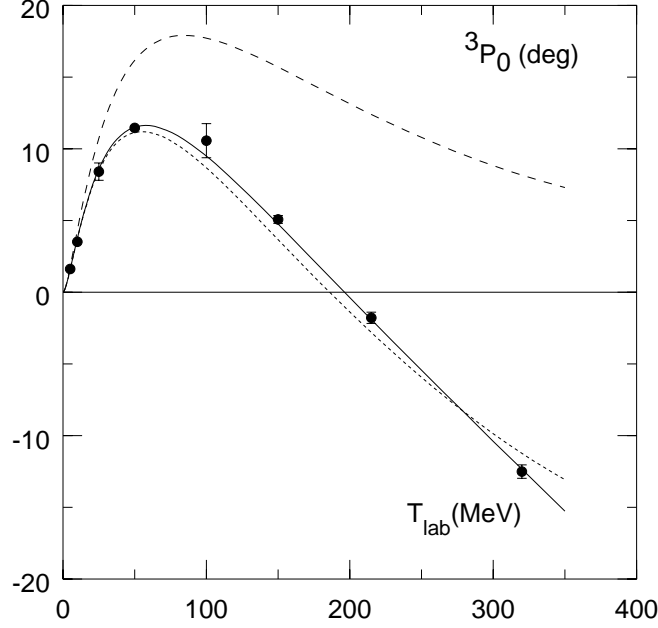


FIGURE 1. 3P_0 phase shift calculated with OPEP tail for $r > b$ (dashed line), and with either one (dotted) or 3 (solid) short-range interaction terms added.

The importance of OPEP is illustrated in Fig. (1) from the Nijmegen group [7]. Using a potential that vanishes out to $b = 1.4$ fm and incorporates OPEP plus some two-pion-exchange potential beyond that value leads to the dashed curve. Clearly, the shape of the phase shift is correct. Adding a smooth background contribution from a short-range potential ($r \leq 1.4$ fm) produces the dotted curve, while fine tuning leads to the solid curve. All of the “shape”, however, is produced by pion exchange, which is hardly a surprise given that the pion is the lightest of the mesons exchanged between two nucleons.

An obvious question is whether a 1-2 MeV uncertainty is a serious handicap in understanding the physics. Alternatively, if one wishes to probe the nuclear force by examining trinucleon properties, what level of calculational accuracy is a reasonable requirement? The fundamental problem is determining the structure of the N - N force, and this is impossible to achieve using only the N - N scattering data. Imagine that some N - N phase shift is known at all energies and with infinite accuracy (neither assumption is true), and that there is no bound state. Under these idealized conditions a potential $V(r)$ (where r is the separation of the two nucleons) can be deduced that in the Schrödinger equation will reproduce the phase shift. Unfortunately, one can also deduce a $V(r, p)$ (where p is the relative nucleon momentum) that reproduces that phase shift equally well. On-shell (free-nucleon)

scattering cannot produce a unique potential. This led to the idea that making the nucleons “off-shell” by placing them in a bound system with a third nucleon might provide enough additional information to fix the potential, since $V(r)$ and $V(r, p)$ defined above will definitely produce different tritons. This is one aspect of what has become known as the “off-shell problem”.

We can estimate the uncertainties by noting that the N - N system (with potential V) feels the presence of the third nucleon only through the action of another V and the effect should scale as V^2 , which has the wrong dimensions. Another related off-shell problem is that the motion of a pion propagating between nucleons is conventionally specified only by its transferred momentum, \vec{q} , while its transferred energy, q_0 , is replaced by other variables such as $p^2/2M$. This hints that the effective off-shell interaction scale is set by $\Delta H = V^2/Mc^2$, which is correct [8] in spite of the intuitive derivation. Because V^2 contains terms linking three nucleons together and because of the $1/c^2$, this effect is at the same time a three-body force, an off-shell effect, and a relativistic correction. Using reasonable numbers for the triton we estimate $\langle \Delta H \rangle \sim 0.5$ - 1.0 MeV. Thus the previously noted calculational uncertainties (~ 1 - 2 MeV) are unacceptably large, and calculational errors $\lesssim 100$ keV (which is approximately 1% of the binding energy) are required in order to investigate the three-nucleon effects discussed above. In addition, 1% absolute experiments are extremely difficult and uncommon. Consequently, 1%-error calculations, known variously as “exact”, “complete”, or “rigorous”, have become the standard of the field. The ability to achieve this has become our field’s major success story.

THREE-NUCLEON CALCULATIONS

The types of problems attacked and the period during which success was achieved are shown in Fig. (2) and Table 1 [9]. There are four regions of energy illustrated

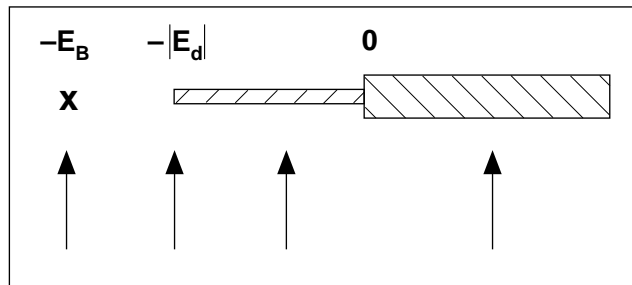


FIGURE 2. Energy spectrum of ${}^3\text{H}$.

in Fig. (2) (by arrows) that conveniently encompass the three-nucleon problem: (1) the trinucleon bound states (a pole at $-E_B$); (2) zero-energy nucleons scattering from the deuteron; (3) N - d scattering below deuteron-breakup threshold (viz., zero total energy); (4) N - d scattering above breakup threshold. These problems were solved at the 1% level at times indicated in Table 1. The Los Alamos-Iowa

group was fortunate enough to have participated in half of the entries (top half) in the table, beginning with the ^3H bound state in 1985 [10] and using only N - N forces, then adding a 3NF, and finally solving ^3He in 1987 (which includes a p - p Coulomb interaction) [11]. Scattering lengths were calculated a few years later [11]. The bound-state problems are relatively easy, however. Scattering below breakup threshold [12] is nearly an order of magnitude harder than a bound-state problem, and above-breakup scattering is nearly an order of magnitude harder still [13]. Above-breakup p - d scattering is a very recent development [14].

TABLE 1. Complete three-nucleon calculations:
“◆” indicates calculations from mid-late 1980’s;
“★” indicates calculations from the early 1990’s;
“●” indicates calculations from early-mid 1990’s;
“■” indicates very recent calculations.

Type	NN Force	NN + 3NF	Coulomb
$E = -E_B$	◆	◆	◆
$E_{Nd} = 0$	★	★	★
$E < E_{th}$	●	●	●
$E > E_{th}$	◆	●	■

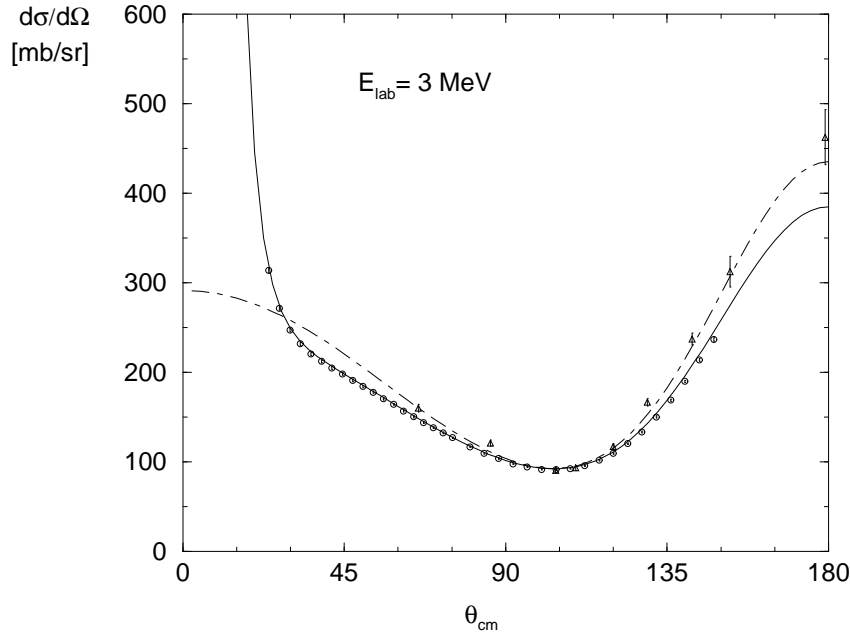


FIGURE 3. N-d scattering at 3 MeV.

A particularly lovely example of this progress is shown in Fig. (3), obtained from the Pisa group [12]. Elastic scattering of 3 MeV nucleons (just below breakup threshold) from deuterons is calculated and compared to data. The solid curve

(p - d) agrees superbly well with the dense, accurate data, while sparser n - d data agree well with the (dashed) calculated values. Note the large Coulomb effect at the forward and backward angles. This plot is rather typical of differential cross sections: they are insensitive to the details of the nuclear force and agree very well with data. Most spin observables, such as tensor analyzing powers, also agree well with data.

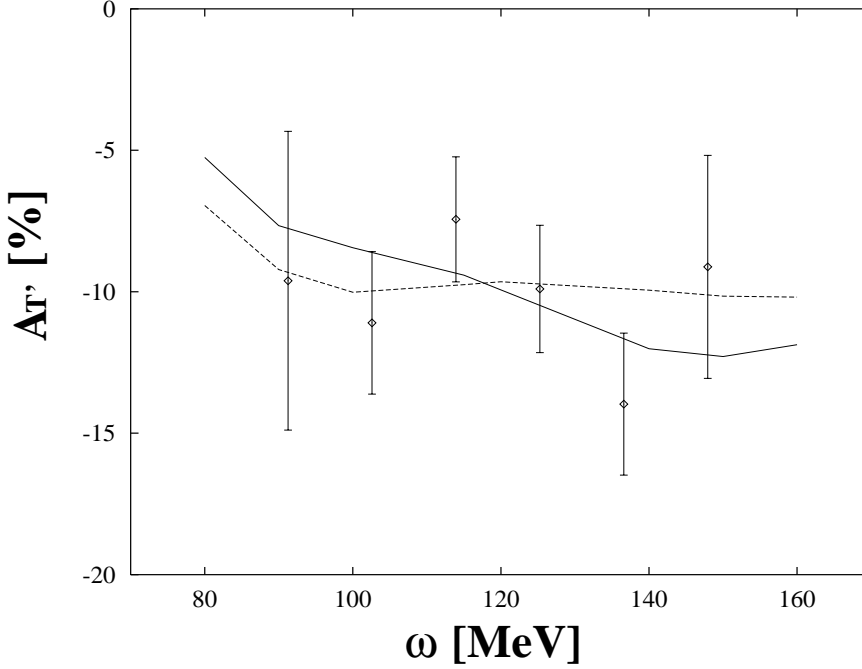


FIGURE 4. The spin-dependent asymmetry $A_{T'}$ in the reaction ${}^3\overrightarrow{\text{He}}(\vec{e}, e'n)pp$. The solid curve depicts the full calculation, while the dashed curve lacks final-state interactions.

Figure (4) shows a very recent calculation [15] of an electromagnetic spin observable, $A_{T'}$, in the reaction ${}^3\overrightarrow{\text{He}}(\vec{e}, e'n)pp$. The ${}^3\text{He}$ target is polarized along the direction of electron momentum transfer, and the electrons are longitudinally polarized. This spin-dependent asymmetry in a response function is proportional to G_M^n (neutron magnetic form factor) in the most naive description of the reaction. That description is based on the observation that s-waves dominate between the nucleons in ${}^3\text{He}$. In that case the two protons are required by the Pauli principle to have spins anti-aligned, and the entire spin of the nucleus is carried by the neutron. The protons do contribute to the reaction because the tensor force modifies the simple s-wave picture and the protons' spins will be aligned in D-states, and can contribute to the asymmetry through final-state p - n charge-exchange reactions. The figure illustrates the Bates data [16] compared to two theoretical calculations: the full calculation (solid curve) and a calculation (dashed curve) that neglects all final-state interactions. The latter calculation would be typical of what was available until very recently, which illustrates both the difficulty of the calculations and the progress that has been made.

I would like to summarize this part of my talk as follows:

- We can now accurately calculate three-nucleon properties. Most of these properties, such as differential cross sections and most spin observables (e.g., the tensor analyzing power, T_{22} [4]), agree well with data and depend only weakly on a 3NF. Electromagnetic calculations are very difficult and are the state-of-the-art.
- Spin-isospin degrees of freedom are the biggest impediment to few-nucleon calculations.
- Many different techniques are now successfully employed in performing calculations [3].
- 1% accuracy is needed in order to disentangle the physics.
- The most demanding problems drive the progress, and Bates problems are of this type.

THREE-NUCLEON FORCES

Three-nucleon forces are small, as we argued earlier for a very special case. In fact that argument holds for the whole class of such forces, as we shall see. If they are so small, are they really necessary, or even interesting? The most modern potentials produce ^3H bound states that are underbound by up to 1 MeV. This defect can be compensated by the addition of a 3NF. Nevertheless, I do not consider this to be very compelling evidence for three-nucleon forces. Are such forces just “theorists’ toys” or is there more compelling experimental evidence?

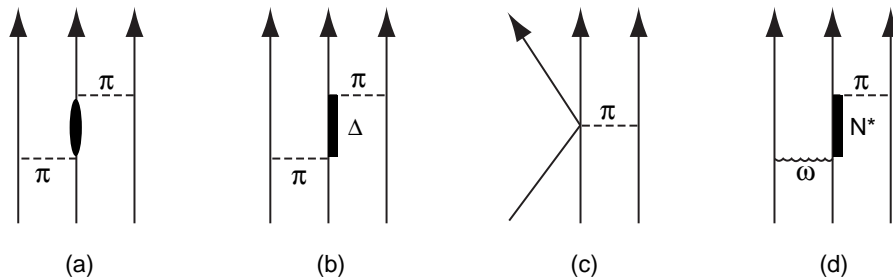


FIGURE 5. Mechanisms that contribute to three-nucleon forces. Two-pion-exchange forces are shown generically in (a), and the important isobar contribution in (b). Chiral perturbation theory predicts a large contribution of the type shown in (c), a specific mechanism of that type being displayed in (d).

In order to answer this question, we must first establish the credentials of the physics underlying the various models of such forces, which are relatively few in number. The longest-range mechanisms are those based on 2π -exchange, and these

have been extensively investigated. Figure (5a) illustrates the generic force of this type, while Fig. (5b) shows the single most important ingredient (other ingredients are also important). The history of this field is depicted in Fig. (6), a diagram showing the evolution of these forces, all of which are field-theory based. Time runs vertically and long lines indicate the oldest forces. Near the bottom are the primitive models (PM). The august Fujita-Miyazawa model [17] (FM) is based on Δ -isobars, as is its offshoot the Urbana-Argonne model [18] (UA). To the left are the models based on chiral symmetry, including the Yang model [2] (Y) (the first of this type, published in 1974) and the Tucson-Melbourne model [19] (TM), the oldest such model still in use. The more recent models based on relativistic field theories (RFT) are the Brazil [20] (BR) and RuhrPot [21] (RP) models. Finally, the Texas model [22] (TX) is based on chiral perturbation theory. It is clear from this history that the two key ingredients of 3NFs are:

- adequate phenomenology (such as isobars).
- imposing chiral constraints.

How does one accomplish this?

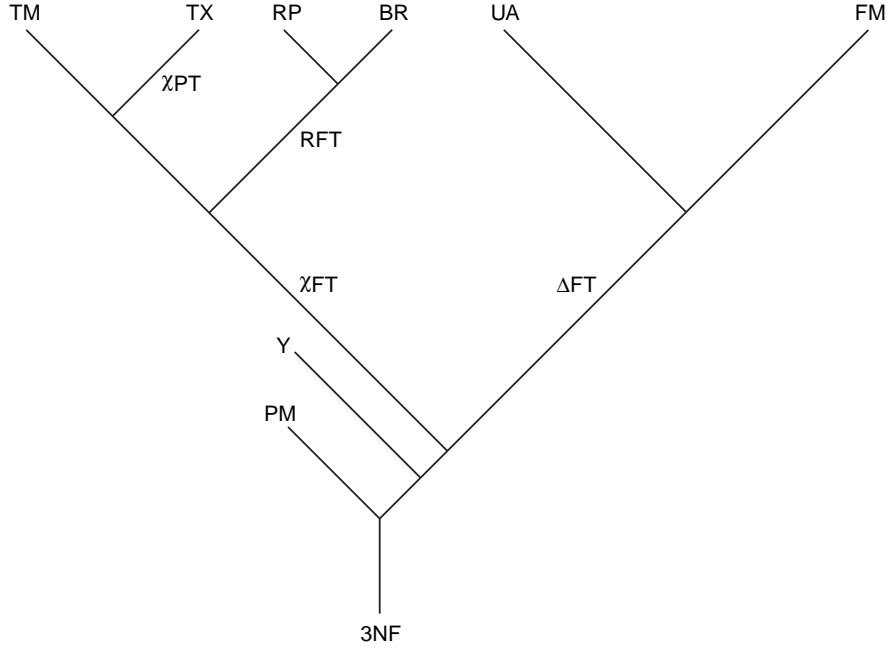


FIGURE 6. Cladogram [23] of 2π -exchange three-nucleon-force models, showing their history with a vertical time line, together with the properties that characterized their development.

It is believed that the theory underlying the strong interactions is QCD. The “natural” degrees of freedom of this theory are quarks and gluons. We aren’t re-

quired to use these degrees of freedom, however, and traditional nuclear physics uses effective (observable) degrees of freedom: nucleons and pions. One can imagine freezing out all other particles and constructing a theory in this compressed Hilbert space, in the fashion of (Feshbach) [P,Q] reaction theory [24]. Although the resulting operators can be quite complicated, chiral symmetry, that most important ingredient residing in QCD, can be implemented in the new theory. This “QCD in disguise” is better known as chiral perturbation theory, and applies to both particles and nuclei [25].

Only one aspect of that theory is needed here: dimensional power counting [25]. The latter is a kind of (not obvious!) dimensional analysis based on only two QCD internal energy scales. The first scale is f_π , the pion decay constant (~ 93 MeV), which controls the Goldstone bosons and specifically the pion. The second scale is the energy above which we agree to freeze out all excitations, $\Lambda \sim 1$ GeV, and is the scale appropriate to the QCD bound states, such as the nucleon, ρ and ω resonances, etc. Using these scales, it can be shown [26] that a given term in a Lagrangian should scale as:

$$\mathcal{L}^{(\Delta)} \sim \frac{c}{f_\pi^\beta \Lambda^\Delta} (\text{times various fields}).$$

Two important properties are that the power Δ (used to classify Lagrangian terms) satisfies $\Delta \geq 0$ (which is a not very obvious chiral-symmetry constraint), while the dimensionless constant c satisfies $|c| \sim 1$, the condition of “naturalness” (an even less obvious constraint). Because freezing out degrees of freedom results in effective interactions with unknown coefficients, the latter condition is the only handle we have on reasonable values for those constants.

This formal scheme can be implemented in nuclei to estimate the size of various contributions to potential energies (among others). An additional nuclear scale is required, the effective momentum or inverse correlation length, which is given by $Q \sim m_\pi c$, where m_π is the pion mass. Then it can be shown that [25]

$$\langle V_\pi \rangle \sim \frac{Q^3}{f_\pi \Lambda} \sim 30 \text{ MeV/pair},$$

$$\langle V_{3NF} \rangle \sim \frac{Q^6}{f_\pi^2 \Lambda^3} \sim 1 \text{ MeV/triplet}.$$

The latter relationship can also be written as $\langle V_{3NF} \rangle \sim \langle V_\pi \rangle^2 / \Lambda$, which is equivalent to the expression we developed earlier (since $M \sim \Lambda$) and is also the correct size to explain the ^3H binding discrepancy. The use of χPT is finally leading to a consensus on 2π -exchange 3NF terms, and a “standard” model of the 3NF is within reach. All such terms in leading order of χPT have been calculated, although some of them have not yet been implemented.

Several of these terms have been checked by testing the tail of the N - N potential against the set of p - p data. That tail is calculated by using the same Lagrangian

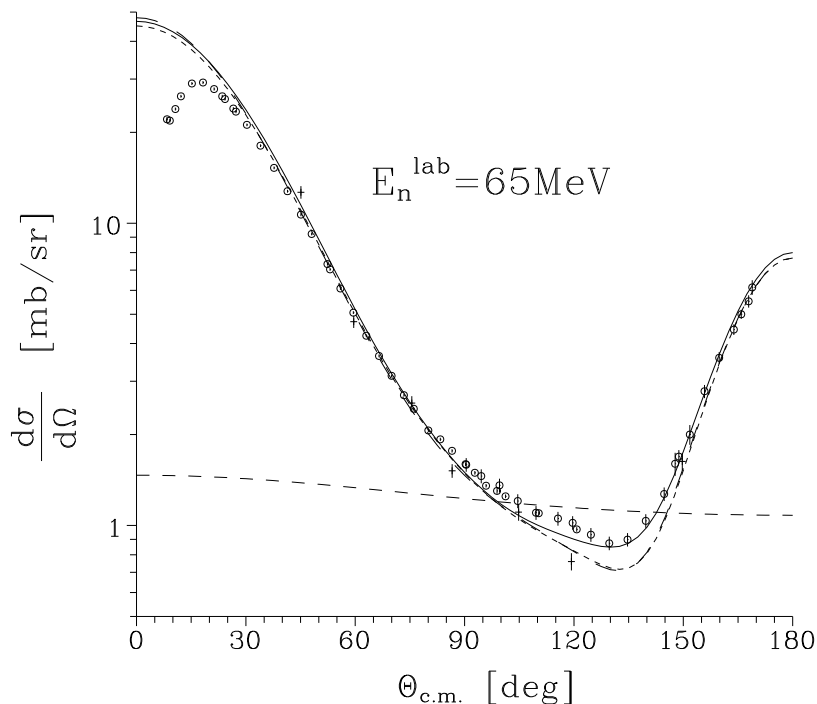


FIGURE 7. Differential cross section for 65 MeV proton-deuteron scattering, showing calculations with N - N forces only (dashed lines), a full calculation that includes the TM 3NF (solid line), and an estimate of the effect of the 3NF alone (long-dashed line).

building blocks that are used to calculate π - N scattering and the 2π -exchange 3NF. Important elements of the 2π -exchange N - N force were verified [27], which validates the corresponding terms in the 3NF.

In addition to the ^3H (^3He) binding discrepancy, there is one other piece of experimental evidence for a 3NF that is much stronger. The Sagara discrepancy [28] is illustrated in Fig. (7), which shows p - d elastic scattering at 65 MeV. Ignoring the forward direction (where the Coulomb interaction plays a significant role), the agreement is very good between calculations with an N - N force only (dashed lines) and the experimental data except in the diffraction minimum. Adding the TM 3NF produces the solid curve, which is in fairly good agreement with experiment in the minimum. The small 3NF effect is depicted by the long-dashed line, which follows from keeping only those terms linear in the 3NF. This behavior is very reminiscent of Glauber scattering, with a dominant single-scattering contribution falling rapidly with angle until the smaller double-scattering term (which has a reduced slope) becomes significant. This is rather strong evidence for a 3NF, and it persists to higher energies.

Our final topic is the extension of 3NFs beyond 2π -exchange. Chiral perturbation theory predicts that there are two mechanisms that have pion range in one pair

of nucleons and short range in a second pair, and they should be comparable in size to the 2π -exchange mechanisms. The generic force in χ PT is shown in Fig. (5c), and a particular example (the so-called d_1 -term) is illustrated in Fig. (5d). All mechanisms affect the ${}^3\text{H}$ binding energy, so this is a poor test of a *specific* mechanism. A tedious examination of low-energy observables [29] finds that the d_1 -mechanism makes a potentially large contribution to the n - d asymmetry, A_y . This observable at 3 MeV is depicted in Fig. (8). The calculation with only N - N forces is the solid line, which is about 30% lower than the data. The long-dashed curve includes the effect of the TM force, which accounts for only about 1/4 of the discrepancy. Adding the d_1 -term in the 3NF with a dimensionless coefficient, $c_1 = -1$, produces the short-dashed curve. The size and sign of that coefficient are unknown, and the sign was chosen to move the prediction upward. Although it appears that a choice of $c_1 = -3$ (and quite acceptable in size) would resolve the problem, the algorithms used in our codes failed to converge for such a value, and that final conclusion could not be checked at the time this manuscript was written.

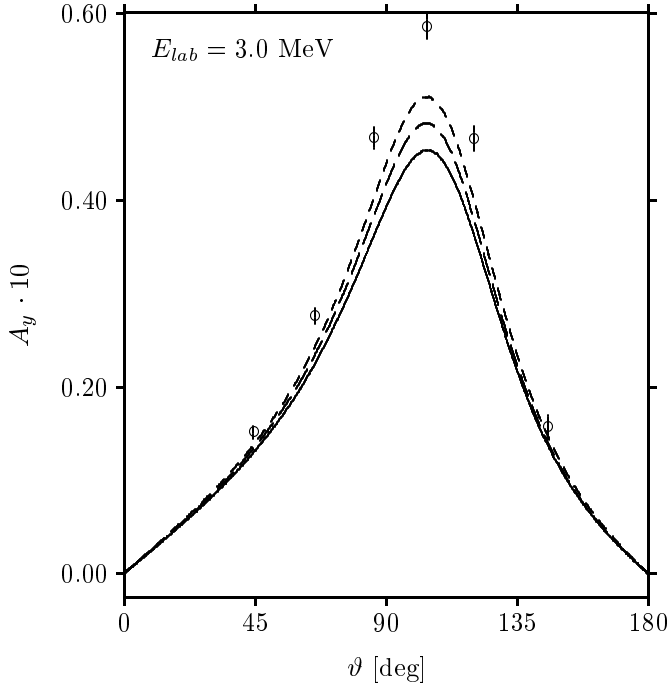


FIGURE 8. The asymmetry, A_y , for 3 MeV neutron-deuteron scattering, calculated using N - N forces only (solid), incorporating the TM force (long-dashed), and further adding a d_1 -type force (short-dashed).

Nevertheless, it appears that this mechanism could resolve the low-energy A_y puzzle, which has existed for many years and in many forms, for both p - d and n - d scattering and in electromagnetic reactions [30]. It remains to be seen whether this

mechanism is compatible with the $A > 3$ bound states and other data.

We summarize this section as follows.

- Most three-nucleon observables are insensitive to 3NFs.
- 3NFs are small in size but appear necessary to reproduce the ${}^3\text{H}$ binding energy, the Sagara discrepancy, and the A_y puzzle.
- Chiral symmetry provides a unified approach to 3NFs; power counting identifies dominant mechanisms.
- The leading-order (dominant) 2π -exchange 3NFs have been calculated; they have large isobar contributions.
- New short-range plus pion-range mechanisms may resolve the low-energy A_y puzzle.
- Although much remains to be investigated, a consensus appears to be developing for the bulk of 3NF terms, and a “standard model” of 3NFs may be possible in the near future.
- The basic building blocks of 3NFs have been recently validated by verifying the corresponding elements in the tail of the N - N potential.

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